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ANALYSIS

Least-cost management of nonpoint source pollution: source reduction versus interception strategies for controlling nitrogen loss in the Mississippi Basin☆

Marc O. Ribaudo *, Ralph Heimlich, Roger Claassen, Mark Peters

Economic Research Service, 1800 M Street NW, Washington, DC 20036-5831, USA

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Abstract

Nutrient pollution is one of the major sources of water quality impairments in the U.S. Agriculture is a major source of nutrients. Two alternative strategies for reducing nutrient loads from cropland are to reduce fertilizer application rates and to filter nutrients coming off cropland with restored wetlands. These two approaches are evaluated in the Mississippi Basin, where nutrient loadings to the Gulf of Mexico have caused a large zone of hypoxic waters. Because of the easement and restoration costs of wetlands, a fertilizer standard was found to be more cost effective than restoring wetlands for achieving a water quality goal up to a particular level of total nitrogen loss reduction. Beyond this point, wetland restorations are more cost-effective. Published by Elsevier Science B.V.

Keywords: Economic model; Economic welfare; Fertilizer; Hypoxia; Nutrients; Wetlands

Nutrients are a major source of water quality impairments in the US. EPA reports that nutrient pollution is the leading cause of water quality impairment in lakes and estuaries, and is the second leading cause in rivers (US Environmental Protection Agency, 1998). Nitrogen and phosphorus can accelerate algal production in receiving surface water, resulting in a variety of problems

☆ This paper is based on the research conducted for the Gulf of Mexico Hypoxia Assessment managed by the White House Committee on Environment and Natural Resources. The effort included a series of six interrelated reports examining different aspects of the hypoxia issue. The authors were part of the research team, led by Otto Doering of Purdue University, that evaluated the social and economic costs and benefits of methods for reducing nutrient loads to the Gulf. The full report is available from the National Oceanographic and Atmospheric Administration (NOAA). The views expressed in this paper are those of the authors and do not necessarily reflect those of the US Department of Agriculture or the Economic Research Service.

* Corresponding author. Fax: + 1-202-6945776.

E-mail address: mribaudo@ers.usda.gov (M.O. Ribaudo).

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including clogged pipelines, fish kills, and reduced recreational opportunities (US Environmental Protection Agency, 1998). Water bodies affected by nutrient pollution range from small lakes and reservoirs to bodies of national significance such as the Chesapeake Bay and Gulf of Mexico. Agriculture is a major source of nutrient pollution. Monitoring in the National Water Quality Assessment Program found that the highest concentrations of nutrients in streams occurs in agricultural basins (US Geological Survey, 1999). High concentrations of nitrogen in agricultural streams are correlated with nitrogen inputs from fertilizers and manure used for crops and from livestock wastes (US Geological Survey, 1999).

Two basic strategies can be taken to reduce nutrient loads to surface waters from cropland. One is to induce changes in the way nutrients are managed on the field. The second is to intercept nutrient-laden runoff and filter out the nutrients before they reach surface waters. There is much literature on the costs of reducing nutrient runoff from fields and a growing literature on the effectiveness of interception strategies such as wetland buffers and vegetative filter strips. However, there has been little comparison of the cost-effectiveness of the two approaches.

This paper uses a mathematical programming model to compare the two alternatives for reducing nitrogen loads to the Gulf of Mexico. A so-called 'Dead Zone' has become a dominant feature of the northern Gulf of Mexico, attributed largely to nitrogen loads from the Mississippi River (Rabalais et al., 1996). Agricultural activities are a major source of nitrogen in the Mississippi Basin (Goolsby et al., 1999). Because of the geographic scale of the problem, the impacts of any policy to reduce nutrient loads from agriculture is going to have a variety of impacts that should be considered in a policy assessment. These include impacts on prices, impacts on agricultural externalities besides nutrients (such as erosion and wildlife habitat), and impacts on production and agricultural externalities outside the target region.

This paper contributes to the literature by considering off-site interception strategies as an alternative to on-site nutrient management in a framework that assesses other important consequences of policy. We find that reducing nitrogen fertilizer use is less costly than wetland restoration up to a particular level of total nitrogen loss reduction. Beyond this point, wetland restorations are more cost-effective. We also find that both policies have important consequences for environmental quality besides nitrogen pollution, both inside the target region and out.

1. Background

The Northern Gulf of Mexico's zone of oxygen-deficient water represents one of the largest hypoxic zones in the western Atlantic Ocean (Rabalais et al., 1997). At its peak, this zone stretches along the inner continental shelf from the Mississippi Delta westward to the upper Texas coast, covering about 7000 sq. miles.

The hypoxic zone is caused by the interaction of several features of the northern Gulf. During the summer months, the waters in the Gulf are warm and relatively stable. During this time freshwater inflows from the Mississippi River, which are lighter than salt water, form a layer at the surface that is rich in inorganic nitrogen carried down the river. The warm waters and availability of nutrients greatly increase the primary productivity (eutrophication) of the upper waters. Phytoplankton and organic carbon from zooplankton sink to the bottom and utilize oxygen, either through respiration or decay. Without adequate mixing with the upper waters, dissolved oxygen near the bottom decreases to hypoxic or anoxic levels.

The long-term consequences to biodiversity, species abundance, and biomass in the Gulf are not yet known, but the potential for significant impacts has raised concerns at both the state and federal levels (National Science and Technology Council, 2000). Experience with other coastal areas affected by hypoxia has shown significant reductions in ecological health and deleterious impacts on fisheries (Diaz and Solow, 1999).

Nutrient concentrations in the Mississippi River have increased dramatically in this century (Goolsby and Battaglin, 1995). There are a number of sources of nitrogen in the Mississippi Basin, including municipal and industrial point sources, commercial fertilizer and animal manure used on cropland, septic systems, and atmospheric deposition. Agricultural sources are estimated to contribute about 65% of the nitrogen loads entering the Gulf from the Mississippi Basin, with 50% from fertilizer and 15% from animal waste (Goolsby et al., 1999). USGS estimates that about 90% of the nitrogen discharged by the Mississippi into the Gulf comes from the Ohio River Basin and the Mississippi Basin above the confluence with the Ohio (Goolsby et al., 1999). This area covers much of the Corn Belt, a major crop production region. Another finding is that little nitrogen is lost once it reaches the major tributaries. This means that the location of nitrogen load reduction strategies in relation to the mouth of the Mississippi is not as important as their effectiveness in reducing nitrogen in runoff before it reaches rivers.

2. Strategies for reducing nitrogen loading

The magnitude of the hypoxic zone and the potential impacts on the Gulf ecosystem has led to discussions on what an appropriate policy response might be. Nitrogen loads from agriculture into the Gulf may be reduced by: (1) changing farming practices to use less nitrogen or changing land use to a less nitrogen-intensive activity than agriculture; or (2) by treating the nitrogen-rich runoff from farms before it reaches the rivers and streams in the basin. The literature provides little guidance on which approach might produce nitrogen-reduction goals at least cost, as no previous studies have directly compared the two options. Crosson (1986) and Gianessi et al. (1986) raise the issue of whether off-site controls may be more efficient than on-site management for protecting water resources from agricultural nonpoint source pollution. They argue that uncertainties over the generation and movement of pollutants from fields imply that managing pollutants where they are causing a problem (adjacent to or above threatened waters) might be more cost effective. Using soil erosion as an example, trapping sediment before it enters waterways through sediment traps, such as sediment basins or vegetative buffers, might make more economic sense than managing thousands of hectares of cropland for uncertain sediment-reduction benefits. An empirical evaluation of this question was not conducted.

The types of farming practices that would reduce nitrogen use include reducing application rates of nitrogen fertilizer, shifting to less nitrogen-demanding crops or crops that fix nitrogen, and applying fertilizer at times when the plants need it most (Mitsch et al., 1999). A policy issue is how to induce producers to change their management practices. The cost of a policy depends heavily on the policy instrument and its design. The literature provides some guidance on what general approaches might be best suited for reducing nitrogen loss from fields. The conclusions from much of this work are that environmental performance-based policies (e.g. policies based on a particular nitrogen runoff goal) are generally impractical for nonpoint source pollution, and that design-based policies (e.g. policies directly targeting particular production practices) are more likely to provide cost-effective control (Braden and Segerson, 1993; Ribaudo et al., 1999), particularly when monitoring and enforcement costs are considered. Further, cost-effectiveness is enhanced when the inputs/technologies chosen as policy bases (the aspect of production targeted by a policy) are highly correlated with water quality. In this study, we selected nitrogen fertilizer application as the most practical policy base.

There are a number of policy options for inducing producers to adopt particular management practices, including taxing polluting inputs, subsidizing the use of nutrient management practices, or mandating the use of particular practices. There is an extensive literature reporting on the performance of various approaches for managing nutrients, including taxes, standards, and subsidies. Most of these studies have focused on a very small geographic area (as small as a field or small watershed) and assumed exogenous prices. Welfare impacts are limited to producers and the government, if taxes or subsidies are employed. Examples include Johnson et al. (1991); Taylor et al. (1992); Bernardo et al. (1993); Huang and Lantin (1993); Huang and LeBlanc (1994); Helfand and House (1995); Randhir and Lee (1997) and Vickner et al. (1998). In general, a single input-based policy instrument was not found to be superior across sites with different characteristics for inducing particular outcomes. Site characteristics play a major role in which policy approach is preferred (Taylor et al., 1992).

Johnson et al. (1991) and Randhir and Lee (1997) found that some reductions in nitrogen losses can be accomplished with little loss of profits by changing cropping or management practices (up to 40% in Randhir and Lee). Further reductions, however, reduced producer net returns. Huang and Lantin focused on reducing excess nitrogen applications (beyond plant needs), and found that restricting input use provided the most cost effective control, as opposed to taxing inputs or output. Bernardo et al. (1993) found that area-wide restrictions on nitrogen use were more cost-effective than per-acre restrictions for reducing nitrogen runoff. Randhir and Lee (1997) found that focusing on a single input can have ‘spillover’ impacts on the use of other inputs that might pose their own environmental problems.

Very few studies have looked at nitrogen management at a scale that would influence commodity prices, as would be expected in a policy aimed at the Mississippi Basin. Rendleman et al. (1995) used a CGE model of the US economy to estimate the economic effects of agricultural fertilizer input reductions on individual farm sectors, and on the economy as a whole. Reductions in fertilizer use, achieved through fertilizer restrictions and market incentives, produced nontrivial economic costs to society. The cost savings of a market-based approach over a command and control approach were found to be modest, leading to a conclusion that factors such as enforcement, administration costs, and environmental effectiveness will be important in selecting a chemical input-control policy.

Taylor and Frohberg (1977) used a linear programming model of the Corn Belt to evaluate the partial welfare effects of limiting nitrogen fertilizer application rates. Commodity prices were endogenous in their model. They found that limiting application rates would reduce consumers' surplus and increase producers' surplus. Producers' surplus increased because the price and quantity changes to a large extent occurred in the inelastic portion of the demand curve for corn and soybeans.

An approach for removing nitrogen from agricultural runoff is to use the natural capability of wetlands to filter nitrogen from the water (Mitsch et al., 1999). Wetlands can act as buffers, trapping nitrogen contained in runoff and ‘processing’ it through plant uptake or denitrification to the atmosphere. Restored wetlands provide additional environmental services, including habitat for wildlife (Heimlich et al., 1998). The cost-effectiveness of wetlands as a nitrogen filter depends on the opportunity cost of retiring and restoring land, filtering capacity, and position in the landscape. Restored wetlands not astride the hydrologic pathways of runoff from cropland provide little load reduction, whereas the same wetlands, better placed, could provide substantial reductions in nitrogen loads to surface waters.

An alternative interception strategy is to promote riparian buffers. However, the ability of buffers to filter nitrogen is much lower (Mitsch et al., 1999). A comparison of buffers and wetlands by Doering et al. (1999) found that wetlands are a more cost-effective approach for intercepting runoff than buffers.

The services of wetlands as a water purification system have been well documented (Novotny and Olem, 1994; Mitsch et al., 1999). Wetlands in a demonstration project in Iowa were found to retain from 40 to 95% of influent nitrogen (Mitsch et al., 1999). Restored wetlands can be expected to filter between 10 and 20 g N/m^2 of wetland per year (Mitsch et al., 1999).

Land retirement as a tool for conservation has been implemented in the Conservation Reserve Program, and the economic consequences to the agriculture sector have been studied. The economic consequences of wetland retirement would be similar, at least in kind. The CRP has been found to reduce commodity stocks, leading to higher prices and increased returns on remaining hectares in production (Council for Agricultural Science and Technology, 1995). Decreases in the number of hectares in production can lead to decreases in variable production costs for participating farmers (Council for Agricultural Science and Technology, 1995). Parks and Kramer (1995) evaluated farmer participation in a wetlands restoration program, and found that the cost of achieving acreage targets may increase if the potential environmental services of wetlands are incorporated quantitatively into a bid selection criteria. Wetlands that are cost-effective in providing water quality enhancement may not coincide with wetlands that can be enrolled and restored at least cost. In our study, we do not examine this issue, but target wetlands on the basis of probable water quality enhancement.

3. Empirical model

The analytic tool required to evaluate the economic and environmental impacts of alternative nitrogen reduction strategies in the Mississippi Basin has to have several important features. Prices have to be endogenous, as the Mississippi Basin accounts for a very significant share of the nation's agricultural output. Changes in the costs of production due to nutrient management policies are expected to impact commodity prices. The model has to estimate nitrogen loss from cropland, and ideally estimate the loss of other agricultural residuals as well. Finally, the model has to have some level of geographic disaggregation so that economic and environmental impacts both inside and outside the Mississippi Basin can be estimated.

Our analytic needs are met by the US Agriculture Sector Mathematical Programming (USMP) regional agricultural model (House et al., 1999). The USMP model is a spatial and market equilibrium model designed for general purpose economic and policy analysis of the US agricultural sector. The economic units that can be analyzed with USMP include products, inputs, geographic areas, and supply/demand markets. The model contains 44 products, comprising the principal US crop and livestock products (such as soybeans or hogs for slaughter) and processed products (such as soybean meal or retail cuts of pork).

USMP is linked with regularly updated USDA production practices surveys, the USDA multi-year baseline (US Department of Agriculture, World Agricultural Outlook Board, 1997), and geographic information system databases such as the National Resources Inventory (US Department of Agriculture, Soil Conservation Service, 1994). USMP predicts how changes in farm, resource, environmental, or trade policy commodity demand, or technology will affect regional supply of crops and livestock, commodity prices and demand, use of production inputs, farm income, government expenditures, participation in farm programs, and environmental indicators (such as erosion, nutrient loadings, and greenhouse gases) (Fig. 1).

USMP's geographic units are 45 model regions formed by the intersection of the 10 USDA farm production regions and 20 land resource regions. Markets for inputs such as land, labor, and irrigation water are specified on a USMP-regional level (Fig. 2). Twenty-three other inputs such as fertilizer and seed are modeled with fixed, national level prices. Additionally, land is separated into crop and pasture classes, and labor is specified by family and hired types. While further disaggregation would be useful in evaluating impacts to the agriculture sector and in targeting policies, the level of disaggregation is limited by the scale of the crop production and farming practice survey data used to build the model.

Four types of product final demand markets are specified: domestic consumption, export (foreign consumption), commercial stocks, and government stocks. Production systems are differentiated according to tillage, multi-year crop rotation, dryland/irrigation, government program participation, and other characteristics. Each production activity is an average of production techniques in the geographic area it represents. Various environmental impacts from production are reported, such as nitrogen loss to leaching and runoff, and soil erosion. These indicators are computed using the EPIC biophysical model (Williams et al., 1990). Baseline acreage for the 10 major field crops in the model affirm the importance of the Mississippi Basin as a crop production region (Table 1). USMP has been applied to a variety of issues, including export levels and variability (Miller et al., 1985), trade agreements (Burfisher, et al., 1992), imports (Spinelli et al., 1996), input taxes (Peters et al., 1997), irrigation policy (Horner et al., 1990), ethanol production (House et al., 1993), wetlands policy (Heimlich et al., 1997; Claassen et al., 1998), and sustainable agriculture policy (Faeth, 1995).

4. Nitrogen reduction scenarios

The policies we evaluated with USMP were mandatory nitrogen fertilizer reductions of 10, 20, 30, 40, 50, and 60%, and wetland restorations of 0.4, 2.0, 4.0, and 7.3 million hectares (1, 5, 10, and 18 million acres). We focused on fertilizer restrictions rather than restrictions on nitrogen runoff because such performance-based policies are generally impractical, due to the unobservable nature of runoff (Braden and Segerson, 1993; Shortle and Abler, 1997; Ribaudo et al., 1999). A policy base must be observable to both producers and to policy makers. By adjusting the amount of nitrogen fertilizer reduction or wetland restoration incrementally, USMP can be used to trace out a social marginal cost curve for each of the policy approaches (Table 2).

We divided the 45 USMP regions into two groups: those inside the Mississippi Basin and those outside the basin. Because the USMP regions do not follow watershed boundaries, the allocation is not precise. However, the most important crop-producing regions in the Mississippi Basin are wholly included in the USMP interpretation of the basin.

The fertilizer use restrictions are implemented by constraining total nitrogen fertilizer use in the basin as a whole, rather than uniformly reducing per-acre applications. This presumes a least-cost allocation of control responsibility. Agriculture can respond to the fertilizer constraints by adjusting fertilizer application rates, crop mix, tillage practices, and hectares planted. Changes in prices, social welfare, nitrogen loss, and soil erosion are obtained directly from the model solution. Administration costs are not included in the analysis.

Fertilizer use can be reduced through policy approaches other than restrictions. Fertilizer taxes would produce the same outcome, the only differ-

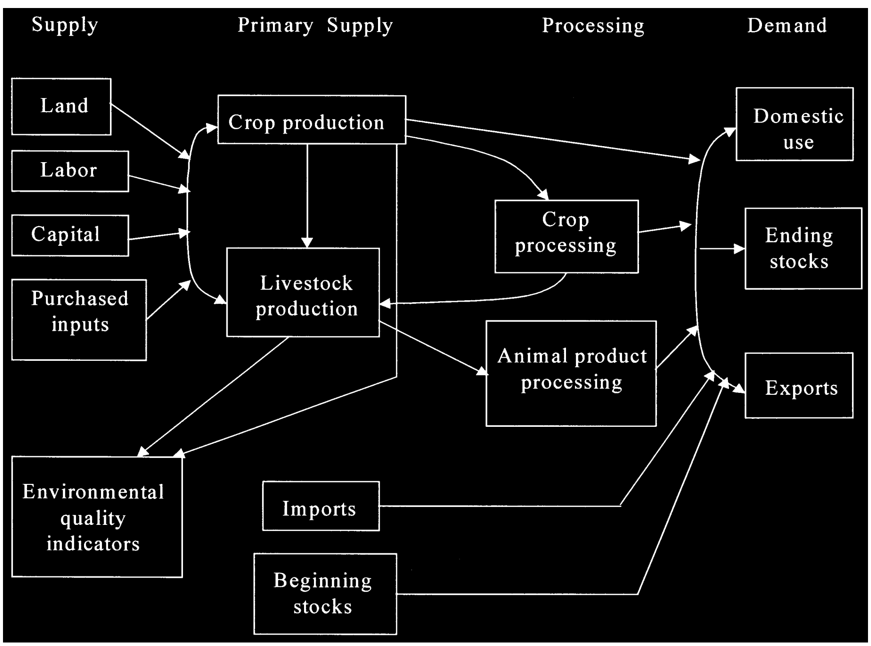
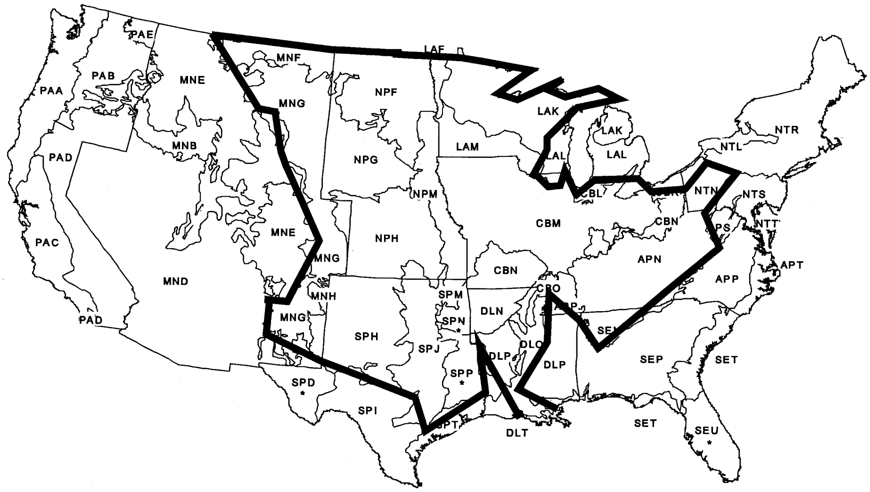


Fig. 1. Schematic flow diagram of the USMP regional agricultural model.



Regions comprising the Mississippi Basin include: NTN, LAF, LAK, LAM, CBM, CBN, CBO, NPF, NPG, NPH, NPM, APN, SEN, DLN, DLO, SPH, SPJ, SPM, SPN, SPP, MNF, MNG, MNH.

Fig. 2. USMP regions. Regions comprising the Mississippi Basin include: NTN, LAF, LAK, LAM, CBM, CBN, CBO, NPF, NPG, NPH, NPM, APN, SEN, DLN, DLO, SPH, SPJ, SPM, SPN, SPP, MNF, MNG, MNH.

ence being in the distribution of welfare impacts between consumers, producers, and taxpayers. A subsidy for reducing fertilizer use is another option. While commonly used in voluntary conservation programs, we do not consider a subsidy because it is contrary to a polluter-pays principle, and subsidies have some undesirable performance characteristics (Ribaudo et al., 1999).

The wetland restoration scenarios employed a hybrid modeling technique combining a screening procedure to identify acreage and production affected by wetland restoration with an impact analysis conducted using the USMP model. Landowners choosing to participate in wetland restoration sell a conservation easement to the government to restore and protect wetlands. The landowner and NRCS develop a plan for the restoration and maintenance of the wetland. The government pays for the easement and 100% of the costs of restoring the wetland. We chose to pay landowners for converting cropland to wetlands rather than requiring them to do so because selection is based on geographic location rather than on the landowners' contributions to the pollution problem.

We targeted wetland restoration in the Mississippi Basin proportional to total nitrogen yield by hydrologic unit (8-digit US Geologic Survey hydrologic unit), as estimated by USGS (Smith et

Table 1
Baseline for USMP

Crop acreage	Million hectares	
	Mississippi Basin	U.S.
Corn	26.2	32.9
Sorghum	3.6	4.4
Barley	1.5	2.9
Oats	1.6	1.9
Wheat	26.6	30.6
Rice	0.6	1.2
Soybeans	20.4	25.2
Cotton	3.5	5.7
Silage	1.7	2.7
Hay	15.7	25.3
Total	101.4	132.8

Table 2
Summary of annual economic impacts[a]

Scenario	N-loss reduction (thousand tonnes)	Welfare costs (million $)	Government costs (million $)	Erosion benefits (million $)	Wetland benefits (million $)	Net welfare costs (million $)	Unit cost ($/tonne)
10% N fertilizer reduction	244	−109		−12		−121	496
20% N fertilizer reduction	517	−348		7		−341	660
30% N fertilizer reduction	738	−844		39		−805	1091
40% N fertilizer reduction	962	−1961		45		−1916	1992
50% N fertilizer reduction	1136	−4165		43		−4122	3628
60% N fertilizer reduction	1463	−8437		98		−8339	5700
0.4 million hectare wetland	97	−1022	137	4	550	−468	4824
2 million hectare wetland	473	−4494	890	16	2751	−1727	3651
4 million hectare wetland	944	−9366	2199	29	5502	−3835	4062
7.3 million hectare wetland	1712	−17 865	4786	51	9904	−7910	4620

[a] Welfare costs include changes in consumer and producer surpluses plus wetland restoration costs. Government costs include restoration and easement costs. Net welfare costs include producer and consumer surplus, wetland restoration costs, erosion benefits, and wetland benefits. Government costs are shown for information only, and are already included under welfare costs.

Table 3
Wetland restoration costs ($/acre)[a]

Region	Fully drained	Cropped wetland
Prairie pothole	100	50
Delta and Southeast	800	600
All other	500	300

[a] *Source:* Economic Research Service, USDA, based on Heimlich, et al. 1998.

al., 1997). Cropland suitable for restoration to wetland was screened using a method similar to the one reported in Claassen, et al. (1998). All cropland on wetland (hydric) soils in the National Resource Inventory (NRI), except wetlands converted in violation of the Swampbuster provisions of the 1985 Farm Bill (CW), is assumed to be eligible for enrollment. The law prohibits such cropland from receiving program benefits. We imposed a restriction that no more than 25% of total cropland in a local area (8-digit hydrologic unit) could be enrolled. This is similar to restrictions in the current CRP and is intended to minimize impacts on local farm economies. Cropland that can be converted at least cost is restored first. Within a hydrologic unit, cropland targeted for potential restoration was converted to USMP regions through a Geographic Information System. We could not locate wetland restoration in the landscape to ensure that it is strategically placed to intercept the maximum amount of runoff, due to the scale of the analysis.

The cost of wetland restoration consists of two components, permanent easement and restoration. Easement costs equal the full opportunity costs of removing productive cropland from production. We assume that landowners are profit-maximizers, and realize no nonpecuniary returns from farming. Restoration costs are the one-time cost of converting cropland back into a functioning wetland. Restoration costs are differentiated by drainage condition and region and calculated using information reported in Heimlich et al. (1998) (Table 3). Restoration costs are annualized using a 4% interest rate and assuming a 50-year planning horizon.

In assessing the wetland restoration scenarios, cropland retired from production to restore wetlands was subtracted from the cropland used in the USMP model's baseline solution in each producing region. Changes in prices and easement costs (lost productivity) were obtained directly from the model results. Restoration costs were calculated separately.

Reductions in nitrogen loss come from two sources, change in land use and filtering runoff. Reductions in nitrogen loss due to changes in land use were obtained directly from the USMP model. The amount of nitrogen filtered from edge-of-field losses was calculated by multiplying hectares of restored wetland by an assumed filtering capacity of 20 g/m^2 of wetland (Mitsch et al., 1999). (Wetland filtering efficiencies as high as 39 g N/m^2 have been observed in field experiments (Mitsch et al., 1999), but should not be expected as a regional average). We assumed that all wetlands perform equally well in their role as nitrogen filters, and that the maximum filtering capacity is achieved.

Wetland restoration has other benefits besides filtering nitrogen, which are not shared by fertilizer reductions. Wetlands provide habitat for wildlife species that support recreational activities such as hunting and fishing, and commercial activities such as fishing and trapping. Wetlands also have a nonuse value. Annualized recreation, commercial, and nonuse values for wetlands were estimated to be about $550 per acre, based on values reported in the literature (Heimlich et al., 1998). Wetland values were not included directly in the model, but were estimated separately.

It should be emphasized that given the complexities of the real world and the assumptions made in developing the model and assembling the data, the reported results are no more than best estimates. However, we believe the direction of the results are reasonable, and offer a useful means for comparing alternative scenarios and for reaching general conclusions about the alternative policies.

5. Results

5.1. Mitigating hypoxia by reducing fertilizer use

A 10% reduction in nitrogen fertilizer use in the Mississippi Basin resulted in a reduction in nitrogen loss from fields of 244 thousand tonnes, or about 5% (Table 2). The economic impacts on the agricultural economy are relatively small. The prices of nitrogen intensive crops, primarily corn and sorghum, increase by 3%, while prices of less nitrogen intensive crops increase by 1% or less. Soybean price remains relatively unchanged. In total, net social welfare (consumer and producer surplus) is reduced by $109 million (Table 2).

Crop producers nationally benefit from the increased prices. Net producer surplus for the agriculture sector rises by $1157 million (Fig. 3). Higher commodity prices reduce consumer surplus by $1266 million. It should be noted that, even though the net returns increase for the agricultural sector as a whole, not all producers benefit. Total crop acreage in production in the Mississippi Basin is reduced by 1.3%, indicating that some economically marginal land goes out of production. In addition, livestock producers are hurt by higher feed prices.

We cannot tell from the model results which changes in management practices (fertilizer application rates, tillage, rotations) play the greatest role in reducing fertilizer use in the Mississippi Basin. In looking at where reductions took place, it is possible to identify those regions that contributed most to the basin-wide reduction goal. Region CBM (primarily Corn Belt states of Iowa, Illinois, Indiana, and Ohio) contributed almost half the reduction in nitrogen loss, far more than from any other USMP region. This is consistent with the USGS finding that the middle and upper Mississippi drainage basins are contributing the largest share of nitrogen reaching the Gulf.

An indication of the stress placed on a region by the fertilizer restrictions is the percentage of cropland that goes out of production. Regions characterized by productive soils and adequate rainfall are likely to be able to have greater flexibility in making adjustments to restrictions on fertilizer use. Cropland in regions with poorer soils or unfavorable climate would be expected to have much less flexibility in making such adjustments. Restrictions in fertilizer use would be expected to force land out of production in these regions first. Regions MNH, SPM, SPH, and SPJ had the greatest percentage reductions in cropland. These regions mostly cover portions of Texas and Oklahoma. Cropland reductions ranged from 4 to 11% in these regions. Most other regions saw reductions of less than 1%.

While a 10% reduction in nitrogen fertilizer use inside the Mississippi Basin reduces edge-of-field

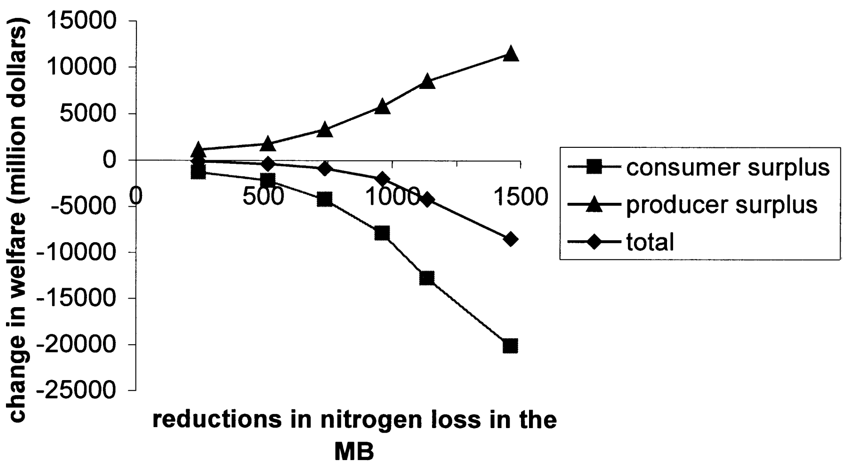


Fig. 3. Welfare changes for fertilizer-reduction strategies. MB, Mississippi Basin.

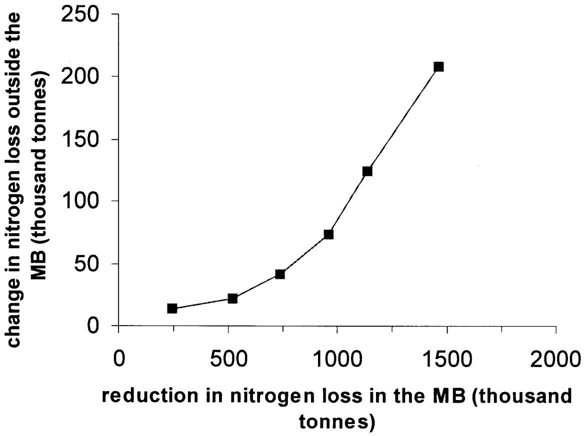


Fig. 4. Changes in nitrogen loss outside the Mississippi Basin in response to fertilizer restrictions within the basin. MB, Mississippi Basin.

nitrogen loss within the basin, nitrogen losses outside the basin are estimated to increase by about 14 thousand tonnes, or 1% (Fig. 4). This is due to more intensive production brought about by higher commodity prices. Water quality outside the basin may be degraded by the increased nitrogen runoff. Such a result points out the importance of taking a global rather than local view of the impacts of policies, and in using a model where prices are endogenous.

Policies that focus only on one of the many consequences of crop production may increase or decrease others. To illustrate these possible changes we assess changes in soil erosion. Changes in cropping practices within the Mississippi Basin result in an increase in sheet and rill erosion in the basin of 1.7% (Fig. 5). Erosion also increases outside the basin by about 0.6% in response to higher commodity prices (Fig. 5). Nationally, damages to water users from increased sediment loads are estimated to be $12 million, based on Ribaudo's estimates of sediment damages to water resources (Ribaudo, 1989). Water quality gains in the Gulf from reductions in nitrogen losses might be offset by degradations of inland waters brought about by increased soil erosion.

The tighter the fertilizer restriction, the more pronounced the economic and environmental effects. As fertilizer use is cut back, production is significantly reduced for most crops. Prices of most commodities rise significantly, with the price of corn rising by over 55% for a 60% reduction in fertilizer use. The only exception is soybeans: soybean acreage actually increases as its use in rotations with other crops rises. Soybeans are a legume that can provide nitrogen to crops following it in rotation. Consumer surplus declines by $2.2 billion with a 20% fertilizer reduction and by $20 billion with a 60% reduction (Fig. 3). Crop producers continue to benefit from the higher prices, with producer surplus rising $1.8 billion for a 20% fertilizer restriction, and $11.6 billion for a 60% reduction (Fig. 3).

As fertilizer use-restrictions are tightened, nitrogen losses within the Mississippi Basin decline (Table 2). Reducing nitrogen fertilizer use by 60% reduces nitrogen losses in the basin by 1.5 million tonnes, or 45%. The regions contributing the greatest reductions in nitrogen loss are CBM and NPH (Nebraska and Kansas), together accounting for 46% of the total basin-wide reduction. Regions losing the greatest percentage of cropland were again SPM, SPH, SPJ, and MNH, covering parts of Texas and Oklahoma, with reductions ranging from 45 to 60%. A second group of regions having significant reductions in cropland also emerges. These include MNF, MNG, NPH, and LAF, with cropland reductions of about 30% each. These regions cover portions of Montana, Kansas, Nebraska, and North Dakota.

As production in the Mississippi Basin declines and commodity prices rise with tighter fertilizer

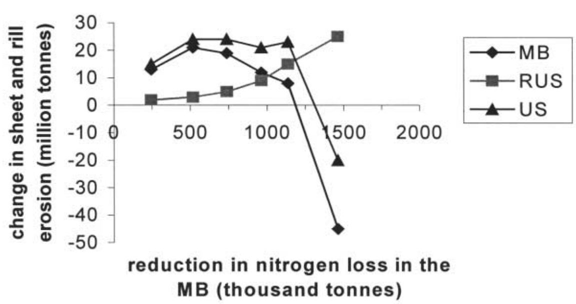


Fig. 5. Changes in soil erosion for fertilizer-reduction strategies. MB, Mississippi Basin; RUS, Rest of U.S.; US, United States.

restrictions, production in the rest of the US intensifies. This causes nitrogen losses outside the basin to increase sharply, to the probable detriment of water quality (Fig. 4). Erosion rates also increase outside the Mississippi Basin (Fig. 5). Within the basin, erosion initially increases as cropping practices are changed. However, as fertilizer restrictions are tightened, greater amounts of marginal land are forced out of production. Even though per-acre erosion rates increase, reductions in crop acreage result in declining erosion beyond a 20% reduction in fertilizer use. For a 60% reduction in nitrogen fertilizer, cropland in production within the basin is reduced by 20%, and erosion is reduced by 30%.

The net costs of the fertilizer restrictions on a per-unit nitrogen reduction basis are reported in Table 2. Net social costs include consumer and producer surpluses and environmental benefits/costs from changes in soil erosion. Unit costs increase sharply as fertilizer restrictions are tightened. For a 60% reduction in fertilizer applications, the unit cost for reducing nitrogen loss in the Mississippi Basin is more than 11 times greater than for a 10% reduction. Adjustments in the agriculture sector needed to cope with required reductions in fertilizer use become more difficult, and costly, as fertilizer use restrictions are tightened.

5.2. Intercepting nitrogen through wetland restoration

An alternative to reducing runoff from fields through fertilizer restrictions is to capture the runoff that leaves fields and filter it through restored wetlands. Wetland restorations of 0.4, 2.0, 4.0, and 7.3 million hectares were examined, targeted to maximize nitrogen reductions.

Restoring 1 million hectares of wetlands was estimated to remove 97 thousand tonnes of nitrogen from field runoff per year. This scenario produces very modest impacts on the agricultural economy. The impacts on crop prices are less than 1%, for all crops. In total, net national social welfare (producer surplus plus consumer surplus plus government costs) is reduced by about $1 billion, or about 0.1% (Table 2). A major difference between this scenario and the fertilizer reduction scenarios is that both consumer and producer surpluses decline (the government shares producer costs by providing rental and restoration payments) (Fig. 6). There are two reasons for this. First, the opportunity cost of the cropland restored to wetlands is significant, being equal to the value of lost production in perpetuity. Second, since most cropland is left to produce unfettered, the impact on commodity prices is much lower. The increases in commodity prices that do occur are insufficient to make up for the lost opportunity costs and the restoration costs.

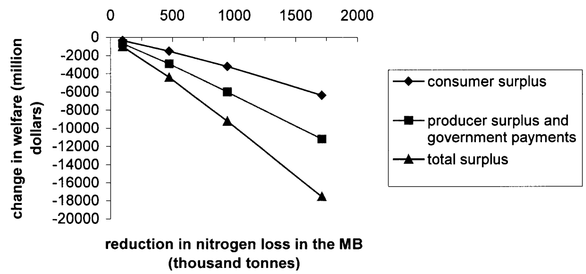


Fig. 6. Changes in welfare for wetlands strategies. MB, Mississippi Basin.

Restoring 1 million hectares of wetlands has little effect on nitrogen losses outside the Mississippi Basin (Fig. 7). The negligible price increases were insufficient to spur much additional production. Soil erosion is slightly reduced within the basin, with little change outside the region (Fig. 8). Changes in erosion result in a net benefit to water users of about $4 million (Table 2). Addi-

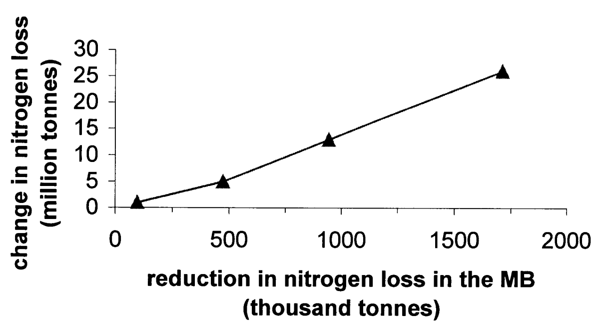


Fig. 7. Changes in nitrogen loss outside the MB, in response to a wetland restoration program in the MB. MB, Mississippi Basin.

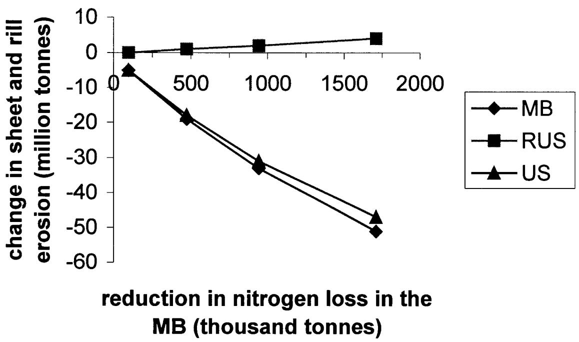


Fig. 8. Changes in soil erosion, by region, for wetlands scenarios. MB, Mississippi Basin; RUS, Rest of U.S.; US, United States.

tional recreation and wildlife benefits of $550 million are generated by the restored wetlands.

As more cropland is restored to wetlands, economic impacts on the agricultural sector became more pronounced. Changes in net social welfare range from a $4.5 billion decrease for the 2.0 million hectare enrollment to a $17.9 billion decrease for the 7.3 million hectare enrollment (Table 2, Fig. 6). Per-acre restoration and easement costs increase as more cropland is restored to wetlands, since the least productive land is converted first, and additional restorations must draw upon more productive cropland. Because commodity prices are not greatly affected, even for the higher amounts of wetland restoration, increases in nitrogen loss and erosion outside the Mississippi Basin remain small, relative to the fertilizer restriction scenarios (Figs. 7 and 8).

The results of the fertilizer reduction and wetland restoration strategies are summarized in Fig.

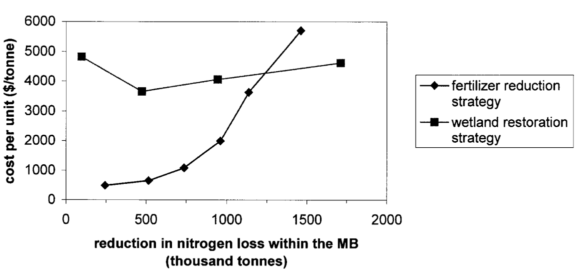


Fig. 9. Summary of nitrogen-reduction strategies. MB, Mississippi Basin.

9. In terms of cost per pound of nitrogen-loss reduction in the Mississippi Basin, wetland restoration costs more than fertilizer restrictions up to about a 1250 tonnes of nitrogen reduced (a 26% reduction in nitrogen loss from the baseline). This is in large part due to the high opportunity cost of converting productive cropland to wetlands. Beyond this point, wetland restoration is cheaper than fertilizer reductions.

An important difference in the wetland restoration policy versus the fertilizer reduction strategy is the impacts felt in regions outside the Mississippi Basin. Production and prices are affected far less by the wetland scenarios, providing less incentive for intensified production outside the basin and its consequences for environmental quality.

6. Conclusions

The choice of on-site fertilizer restrictions or off-site wetland restorations for reducing nitrogen loads to the Gulf of Mexico depends on the level of nutrient reduction that is desired. Our analysis found that on-site fertilizer-based source controls are more cost-effective than off-site, wetland-based interception strategies up to a basin-wide nitrogen-loss reduction goal of about 1.2 million tonnes (26%). The major reasons for the higher cost of wetland restoration are the opportunity cost of retiring cropland and the cost of restoring wetland functions on cropland. Beyond a nitrogen-loss reduction from cropland of 26%, the fertilizer reduction-based strategy becomes more expensive, due to the large reduction in output and increases in commodity prices.

A factor that we could not account for in our analysis is that there is great variation in the potential for wetlands to improve water quality, due largely to topography and landscape position (Mitsch et al., 1999). The greater the land area from which a wetland receives its runoff, the greater the possibility that the capacity for wetlands to filter out nitrogen is approached. Placing a wetland in a part of a watershed that receives little runoff from surrounding cropland does not produce much of a water quality benefit, even if the watershed has a high nitrogen yield. Since we assumed maximum filtering, we likely overestimated the cost-effectiveness of constructed wetlands. Additional information on the relationship between wetland location and filtering would improve the analysis, although it may be difficult to incorporate such information into a model as aggregate as USMP.

The results of our analysis also point out the importance of fully considering the potential spillover effects of a policy. Focusing only on nitrogen losses in the Mississippi Basin could lead to increases in soil erosion within the basin, and increases in both erosion and nitrogen losses outside the basin. A determination of whether potential spillovers are an acceptable consequence of a policy would have an important bearing on its design.

The comparison presented in this paper is relevant for areas where soils are conducive to wetland restoration. In areas where wetland restoration or creation is not practical, other interception strategies might be employed, such as streamside buffers. However, our results are not directly applicable to this strategy.

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